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RESEARCH MEMORANDUM

AN ANALYTIC STUDY OF TURBOJET-ENGINE THRUST AUGMENTATION WITH LIQUID HYDROGEN, PENTABORANE, MAGNESIUM SLURRY, AND JP-4 AFTERBURNER FUELS AND A 220-SECOND IMPULSE ROCKET

By James F. Morris

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON
August 15, 1956

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RESEARCH MEMORANDUM

AN ANALYTIC STUDY OF TURBOJET-ENGINE THRUST AUGMENTATION WITH LIQUID HYDROGEN, PENTABORANE, MAGNESIUM SLURRY, AND JP-4 AFTERBURNER FUELS AND A 220-SECOND IMPULSE ROCKET

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SUMMARY

Thrust augmentation and the accompanying total fuel flow were computed and compared for four afterburner fuels and a rocket. Four turbojet engines burning JP-4 primary fuel and several operating conditions were selected for the analyses. Net thrusts were computed for all engines using choked convergent exhaust nozzles; calculations for complete expansion of combustion products were also made for a high-pressure-ratio engine.

The order in which the afterburner fuels and the rocket performed did not change throughout the study. For any engine and operating condition, fuel consumption for a given augmented thrust ratio increased in the following order: (1) liquid hydrogen, (2) pentaborane, (3) JP-4 fuel, (4) 60 percent magnesium slurry in JP-4 fuel, and (5) 220-second specific-impulse rocket. At stoichiometric fuel-air ratio, augmented thrust ratios for the afterburner fuels decreased in the following order: (1) 60 percent magnesium slurry in JP-4 fuel, (2) pentaborane, (3) liquid hydrogen, and (4) JP-4 fuel.

Liquid hydrogen and pentaborane afterburner fuels gave specific fuel consumptions lower than those of a turbojet engine without afterburning at certain flight conditions.

INTRODUCTION

Altitude, speed, or range of turbojet-powered aircraft may be increased by the use of special fuels. However, some of these fuels give liquid or solid combustion products. Deposits of these products in primary combustors and turbines can cause friction losses, area changes, and poor temperature profiles. Afterburning with high-energy fuels can augment turbojet-engine thrust without introducing problems caused by passing solid and liquid combustion products through the turbine. Quite aside from deposit problems, any afterburner fuel is of interest if it can give more thrust or lower fuel consumption than existing augmentation methods.

Therefore, augmented thrust ratios and fuel-consumption values were computed for four afterburner fuels and a rocket, each used with four turbojet engines burning JP-4 fuel in the primary combustors. All calculations accounted for the nature of combustion products of each fuel. The augmentation methods were compared at take-off and cruise conditions to show the following:

(1) Relative values of thrust augmentation and total fuel flow for a given turbojet engine with afterburning using liquid hydrogen, pentaborane, JP-4 fuel, or a 60 percent magnesium slurry in JP-4 fuel, and with a 220-second specific impulse rocket 3960

(2) Relative performance values of the afterburner fuels and the rocket used with various turbojet engines over a range of flight conditions

The thrust-augmentation calculations were made for four turbojet engines typified by the following data:

Engine	Sea-level static compressor pressure ratio	Turbine-outlet temperature, °R	Turbine blades
A	5.2	1760	Uncooled
B	7.8	1670	Uncooled
C	12.0	1510	Uncooled
D	8.4	2062	Cooled

Augmented net thrust and liquid ratios were computed for all engines operating at sea-level static conditions and at an altitude of 50,000 feet and a flight Mach number of 0.81. These calculations were made for expansion of turbojet-engine and afterburner exhaust products through choked convergent nozzles.

Performances of the four afterburner fuels and the rocket were examined for expansion of combustion products to Mach number 1.0 and to ambient static pressure at the exits of the exhaust nozzles for turbojet engine D. In this case, specific fuel consumption and augmented net thrust ratio were computed for flight at Mach numbers from 0.9 to 2.50 at an altitude of 50,000 feet.

ANALYTICAL METHODS

The methods used to calculate turbojet-afterburner net thrusts for these analyses are the exact nomographic solutions given in reference 1.

These methods use ideal air specific-impulse data for various fuels to compute jet-engine net thrusts for expansion of combustion products to either a Mach number of 1.0 or the ambient static pressure at the exhaust-nozzle exit.

Thermodynamic data relating air specific impulse, ratio of specific heats, and equivalence ratio for ideal combustion of blends of each of the afterburner fuels with octene-1 (JP-4 fuel equivalent) were obtained from references 1 to 4. For afterburner calculations, the combustion products were assumed to be those that would result from burning a blend of the primary (JP-4 fuel) and afterburner fuels. This is actually the case for ideal combustion; it is a good approximation for high combustion efficiencies.

Performance levels for the augmentation methods were compared using the following conventions:

(1) Augmented net thrust ratio: The net thrust for the turbojet engine with augmentation divided by the net thrust of the turbojet engine without afterburning but with the afterburner in place

(2) Augmented liquid ratio: The total fuel flow for the turbojet engine with augmentation divided by the liquid flow for the turbojet engine alone

(3) Specific fuel consumption: The rate of total fuel flow (lb fuel/hr) divided by the corresponding net thrust (lb thrust)

Engine Operating Conditions

Augmented net thrust and liquid ratios were computed for expansion of turbojet-engine and afterburner exhaust products to a nozzle-exit Mach number of 1.0. These calculations were made for four turbojet engines with thrust augmentation using a 220-second specific-impulse rocket and the following afterburner fuels:

(1) Liquid hydrogen

(2) Pentaborane

(3) A 60 percent magnesium slurry in JP-4 fuel

(4) JP-4 fuel

The following engine operating conditions were selected for these calculations: (1) sea-level static, and (2) an altitude of 50,000 feet and a flight Mach number of 0.81.

Specific fuel consumption and augmented net thrust ratio for turbojet engine D were computed for expansion of combustion products to Mach number 1.0 and to ambient static pressure at afterburner exhaust-nozzle exits. These values were obtained for each augmentation method used with engine D operating at an altitude of 50,000 feet and flight Mach numbers of 0.9, 1.27, 1.534, 2.025, 2.37, and 2.50.

Ambient and afterburner-inlet conditions for the four turbojet engines at the selected operating conditions are given in table I. These data were obtained from references 5 and 6 and unpublished results. 3960

Assumptions

The effects of combustion efficiencies for the turbojet-engine primary combustors were included in calculations for this work. For this purpose, combustion efficiency was defined as the ratio of ideal to actual equivalence ratios for a given air specific-impulse value. This is an approximate method, good only for high combustion efficiencies.

The following afterburner-component coefficients were assumed:

(1) Combustion efficiency, 100 percent

(2) Flameholder drag coefficient (ratio of total-pressure drop to approach dynamic pressure), 1.6.

(3) Total-pressure ratio across exhaust nozzle, 0.97

Details of the calculation methods are given in reference 1; therefore, they are not discussed here. However, the assumptions for calculating net thrust using the exact nomographic solutions (figs. 3 to 5 with either 6 or 7 of ref. 1) are as follows:

(1) Values of air specific impulse and ratio of specific heats are constant across the afterburner flameholder. Values of air specific impulse and specific-heats ratio are constant from the end of the afterburner combustion zone to the exit of the exhaust nozzle.

(2) The afterburner cross-sectional area is constant from the inlet (upstream of the flameholder) to the exhaust-nozzle inlet.

(3) All energy and mass additions occur in a manner giving only momentum losses across the combustion zone. The complete afterburner friction loss is represented by flameholder and exhaust-nozzle total-pressure ratios.

RESULTS AND DISCUSSION

The variations of augmented net thrust ratio with augmented liquid ratio for four afterburner fuels and a rocket are shown in figures 1. These values were computed for expansion of turbojet-engine and afterburner exhaust products to a Mach number of 1.0 at the nozzle exit. Thrust augmentation for sea-level static operation with engines A to D is illustrated in figures 1(a) to (d), respectively. Augmentation ratios at an altitude of 50,000 feet and a flight Mach number of 0.81 for engines A to D are shown in figures 1(e) to (h), respectively.

Throughout figures 1 total fuel flows for a given augmented net thrust ratio increase in the following order:

(1) Liquid hydrogen

(2) Pentaborane with condensed boron oxide exhaust products (lower segment)

(3) Pentaborane with gaseous boron oxide exhaust products (upper segment)

(4) JP-4 fuel

(5) 60 Percent magnesium slurry in JP-4 fuel

(6) 220-Second impulse rocket

In all figures, the dotted lines approaching the discontinuities of the curves for pentaborane indicate extrapolation into the region where boron oxide changes from a liquid to a gaseous phase. Recent vapor-pressure data for boron oxide conflict with those used for the reference thermodynamic data for pentaborane (refs. 2 to 4). The transition ranges probably will occur at higher temperatures. When correct data are available, the curves for pentaborane with liquid and gaseous combustion products can be connected properly.

Highest ideal augmented net thrust ratios would occur at fuel-air ratios a little greater than stoichiometric for afterburner fuels in which all compounds react at about the same rate with air. Preferential combustion of magnesium from slurries burning at higher than stoichiometric would yield greater net thrust ratios as the fuel-air ratio approached that which would allow complete reaction of the air with magnesium.

The augmented net thrust ratios at unit equivalence ratio for afterburner fuels (maxima shown in figs. 1) decrease in the following order:

(1) 60 Percent magnesium slurry in JP-4 fuel

(2) Pentaborane

(3) Liquid hydrogen

(4) JP-4 fuel

Attainable thrust augmentation was highest for those engines having lowest turbine-outlet temperatures (lowest primary-combustor fuel flow).

The effects of high flight velocity and increased over-all pressure ratio at an altitude of 50,000 feet caused the increase in augmented net 3960 thrust ratio (figs. 1(e) to (h)) relative to the value at sea-level static conditions (figs. 1(a) to (d)) for a particular engine with a given afterburner fuel.

The influence of flight Mach numbers higher than 0.81 on thrust augmentation was examined for turbojet engine D. This engine design was aimed at future flight plans for high altitudes and flight Mach numbers up to 2.5. Figures 2 and 3 show some effects of flight Mach number on specific fuel consumption and augmented net thrust ratio for the four afterburner fuels and the rocket, each used with turbojet engine D at an altitude of 50,000 feet.

In figures 2, performance levels are given for expansion of combustion products to unit Mach number at the afterburner exhaust-nozzle exit. Figures 3 show results computed for complete expansion of afterburner exhaust gases. The best design would be based on a balance of net thrust against exhaust-nozzle weight, drag, and complexity. For the optimum design, performance values would lie between those given in figures 2 and 3. Parts of figures 2 and 3 showing results for the same augmentation methods are discussed together.

Figures 2(a) and 3(a) reveal that the use of JP-4 fuel in the afterburner of turbojet engine D resulted in an increase of specific fuel consumption in all cases. At a flight Mach number of 0.9, the specific fuel consumption using a choked convergent exhaust nozzle (fig. 2(a)) climbed from 1.27 for no afterburning to 2.17 at an equivalence ratio of 1.0 (augmented net thrust ratio of 1.66). When the flight Mach number reached 2.5, the specific fuel consumption increased from 1.96 at unit augmented net thrust ratio to 2.73 for an equivalence ratio of 1.0 (augmented net thrust ratio of 3.02).

For complete expansion of exhaust products (fig. 3(a)), specific fuel consumption at a flight Mach number of 0.9 varied from 1.21 for no augmentation to 2.06 at unit equivalence ratio (augmented net thrust ratio of 1.64). At a flight Mach number of 2.5, specific fuel consumption increased from about 1.33 to 2.16 as the afterburner equivalence ratio for JP-4 fuel changed from 0 to 1.0 (augmented net thrust ratio of 2.59).

Using a 60 percent magnesium slurry in JP-4 fuel in the afterburner for turbojet engine D at an altitude of 50,000 feet (figs. 2(b) and 3(b)) produced higher net thrust ratios than JP-4 fuel alone (figs. 2(a) and 3(a)). However, at given values of augmented net thrust ratio and Mach number, the slurry always required greater fuel flow.

Pentaborane afterburner fuel (figs. 2(c) and 3(c)) yielded higher augmented net thrust ratios for given values of specific fuel consumption and flight Mach number than did JP-4 fuel (figs. 2(a) and 3(a)). This gain in net thrust was greater for pentaborane combustion products containing liquid boron oxide (lower portions of plots) than for gaseous boron oxide (upper segments).

Low levels of augmentation with pentaborane afterburner fuel gave lower specific-fuel-consumption values than were given by turbojet engine D alone at flight Mach numbers of above about 2.1. As the flight Mach number reached 2.5, a choked convergent exhaust nozzle (fig. 2(c)) yielded augmented net thrust ratios of about 2.0 at lower values of specific fuel consumption than that for engine D without afterburning. For complete expansion of exhaust products (fig. 3(c)), augmented net thrust ratios of about 1.3 were obtained with lower specific fuel consumption than that for the turbojet engine alone at a flight Mach number of 2.5.

Use of liquid-hydrogen fuel in the afterburner of engine D at an altitude of 50,000 feet (figs. 2(d) and 3(d)) generally produced lower specific-fuel-consumption values than were produced with the engine alone. This is true except in the ranges of flight Mach numbers from 0.9 to 1.35 for a choked convergent exhaust nozzle (fig. 2(d)) and from 0.9 to 1.43 for complete expansion of exhaust products (fig. 3(d)). In these regions, specific fuel consumptions for augmentation ratios at and near those for unit equivalence ratio are higher than specific fuel consumptions for turbojet engine D alone.

The following table shows the percent decrease in specific fuel consumption (relative to that for turbojet engine D without afterburning) at several flight Mach numbers for afterburning with liquid hydrogen to produce (1) minimum specific fuel consumption, and (2) unit equivalence ratio (near-maximum thrust augmentation). Corresponding augmented net thrust ratios are also given at the two specified conditions for each Mach number:

Flight Mach number	Minimum sfc				Unit equivalence ratio			
	Decrease in sfc, percent		Augmented net thrust ratio		Decrease in sfc, percent		Augmented net thrust ratio	
	Expansion to Mach 1.0	Complete expansion	Expansion to Mach 1.0	Complete expansion	Expansion to Mach 1.0	Complete expansion	Expansion to Mach 1.0	Complete expansion
0.9	3.5	3.5	1.3	1.2	-5.5	-5.4	1.7	1.7
1.3	6.5	5.7	1.5	1.4	-.75	-1.4	1.9	1.85
1.7	12.0	8.6	1.7	1.6	6.2	2.8	2.1	2.1
2.1	19.0	13.9	2.1	1.8	14.1	7.4	2.5	2.35
2.5	28.5	18.0	2.6	2.0	24.8	12.4	3.2	2.7

Figures 2(e) and 3(e) show that the 220-second impulse rocket used with turbojet engine D required high liquid flow rates compared with those for the afterburner fuels to produce a given augmented net thrust ratio for flight Mach numbers from 0.9 to 2.5 at an altitude of 50,000 feet.

SUMMARY OF RESULTS

Augmented ratios of net thrust and of total fuel flow for four afterburner fuels and a rocket, each used with four turbojet engines burning JP-4 primary fuel, were computed and compared. For these calculations, turbojet-engine and afterburner exhaust products were assumed to expand to a nozzle-exit Mach number of 1.0. The comparisons were made for sea-level static operation and for flight at an altitude of 50,000 feet and a Mach number of 0.81. 3960

Variations of specific fuel consumption with augmented net thrust ratio and flight Mach number at an altitude of 50,000 feet were calculated for the five augmentation methods, each used with an engine having cooled turbine blades. In this case, performance levels were computed for expansion of combustion products to Mach number 1.0 and to ambient static pressure.

Relative performance ratings of the four afterburner fuels and the rocket did not change for all engines and flight conditions that were examined. Total fuel flow to produce a given augmented net thrust ratio increased in the following order for the augmentation methods, each used with a particular turbojet engine operating at given flight conditions:

(1) Liquid hydrogen

(2) Pentaborane with condensed boron oxide exhaust products

(3) Pentaborane with gaseous boron oxide exhaust products

(4) JP-4 fuel

(5) 60 Percent magnesium slurry in JP-4 fuel

(6) 220-Second specific-impulse rocket

Augmented net thrust ratios at stoichiometric fuel-air ratio for the afterburner fuels decreased in the following order:

(1) 60 Percent magnesium slurry in JP-4 fuel

(2) Pentaborane

(3) Liquid hydrogen

(4) JP-4 fuel

The thrust at unit equivalence ratio is very near the maximum for fuels in which all compounds react at about the same rate with air. However, preferential combustion of magnesium would continue to increase thrust augmentation as the slurry fuel flow increased toward the amount that would allow complete reaction of the magnesium and air.

The rocket always gave the highest specific fuel consumption.

Liquid hydrogen and pentaborane afterburner fuels gave values of specific fuel consumption below those for a turbojet engine using JP-4 fuel without afterburning for certain flight conditions.

The attainable augmented net thrust ratio was highest for those engines having lowest turbine-outlet temperatures.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, January 19, 1956

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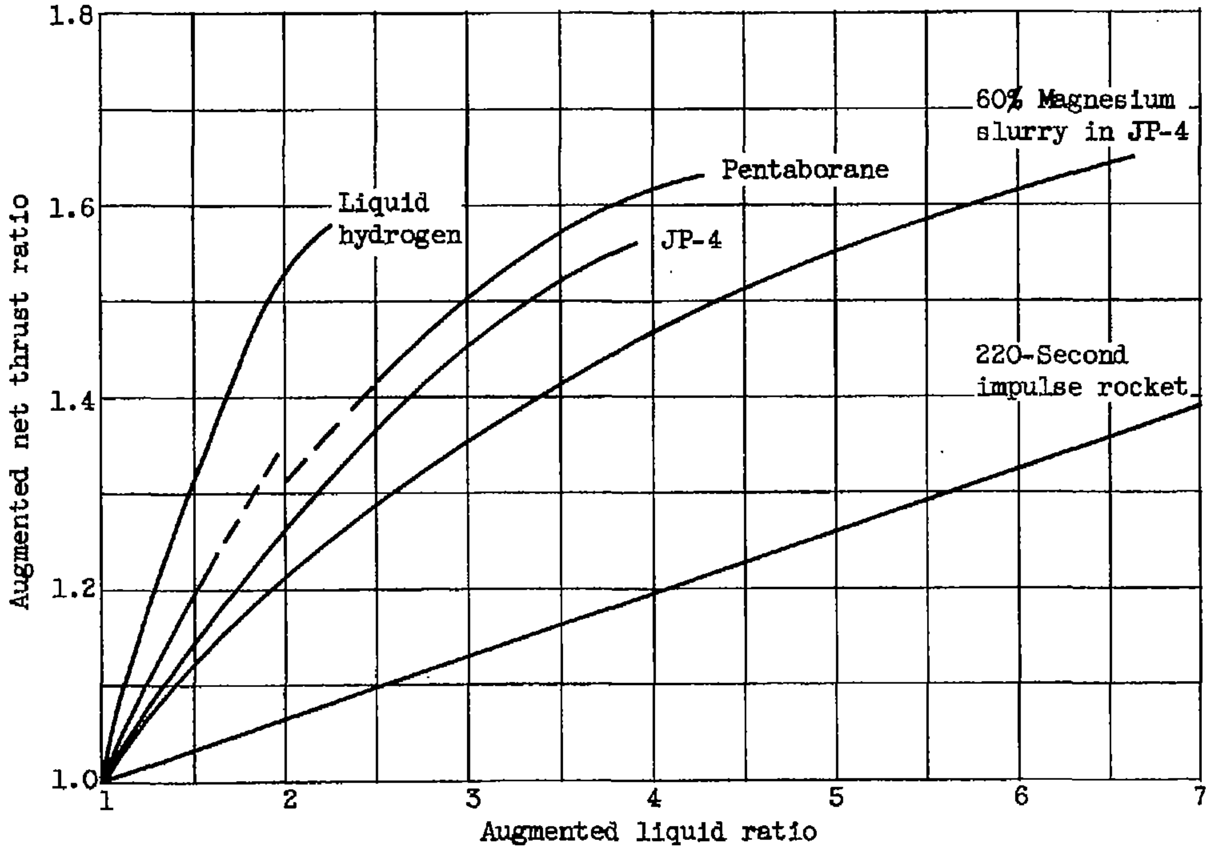
TABLE I. - AFTERBURNER-INLET CONDITIONS FOR THE VARIOUS TURBOJET

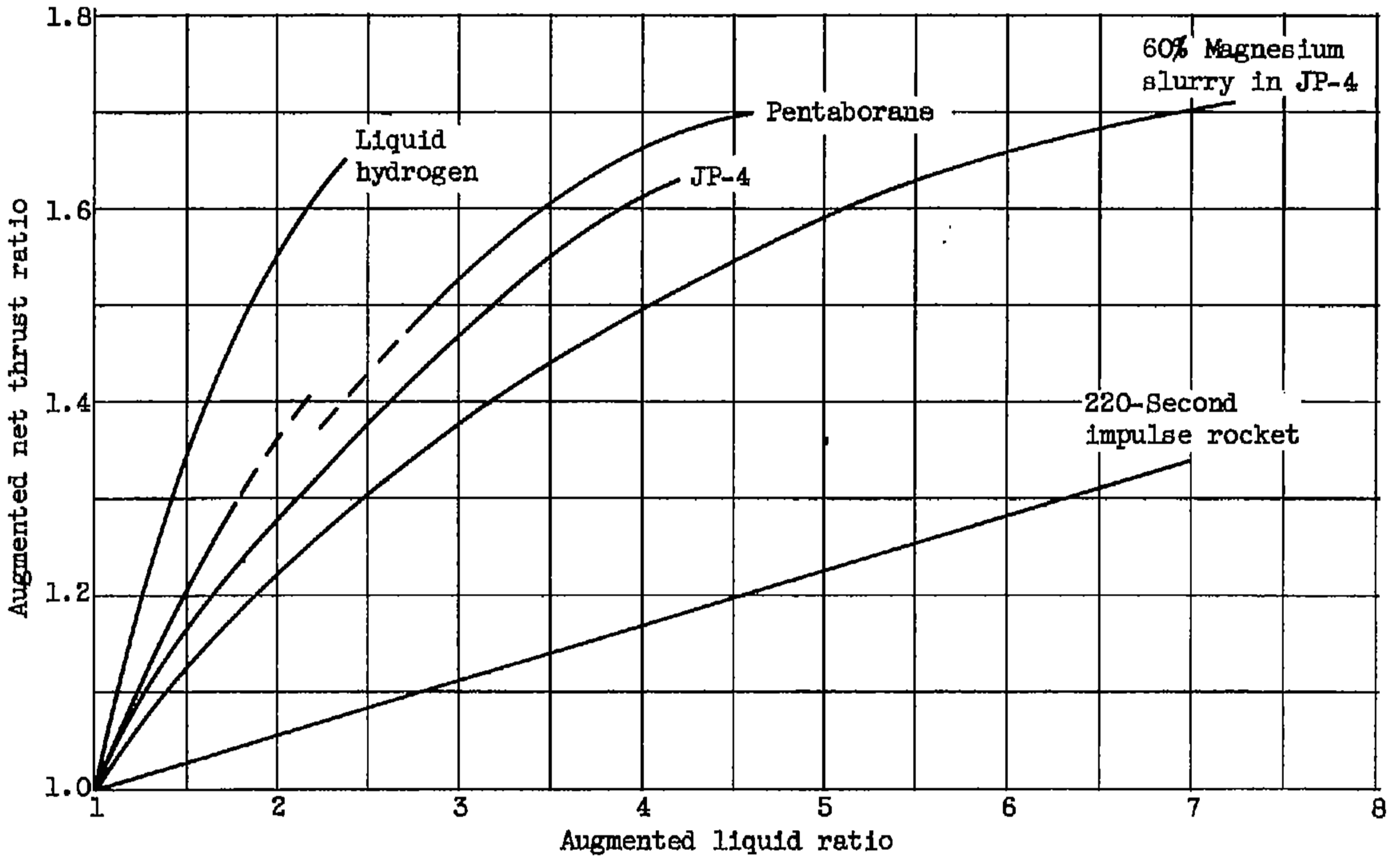
ENGINES AND AMBIENT CONDITIONS

Engine type	Compressor pressure ratio	Altitude, ft	Flight Mach number	Engine-inlet total temperature, °R	Afterburner-inlet total temperature, °R	Primary-combustor combustion efficiency	Ratio of afterburner-inlet total to ambient static pressures	Afterburner-inlet Mach number
A	5.2	0	0	519	1760	0.99	1.98	0.205
		50,000	.81	445	1760	.97	3.25	.209
B	7.8	0	0	519	1670	0.99	2.30	0.220
		50,000	.81	445	1670	.97	3.87	.218
C	12	0	0	519	1510	0.98	2.24	0.185
		50,000	.81	445	1510	.96	4.28	.190
D	8.4	0	0	519	2062	0.99	2.60	0.222
		50,000	.81	445	2110	.98	4.90	.200
			.90	457	2104	.98	5.30	.204
			1.27	520	2062	.985	7.16	.222
			1.534	578	2026	.99	8.94	.236
			2.025	715	1995	.99	13.07	.249
			2.37	835	1989	.99	16.92	.252
			2.50	884	2001	.99	19.04	.246



(a) Engine A; sea-level static conditions.

Figure 1. - Augmented ratios of net thrust and of liquid for four afterburner fuels and a rocket used with turbojet engines operating with choked convergent exhaust nozzles.



(b) Engine B; sea-level static conditions.

Figure 1. - Continued. Augmented ratios of net thrust and of liquid for four afterburner fuels and a rocket used with turbojet engines operating with choked convergent exhaust nozzles.

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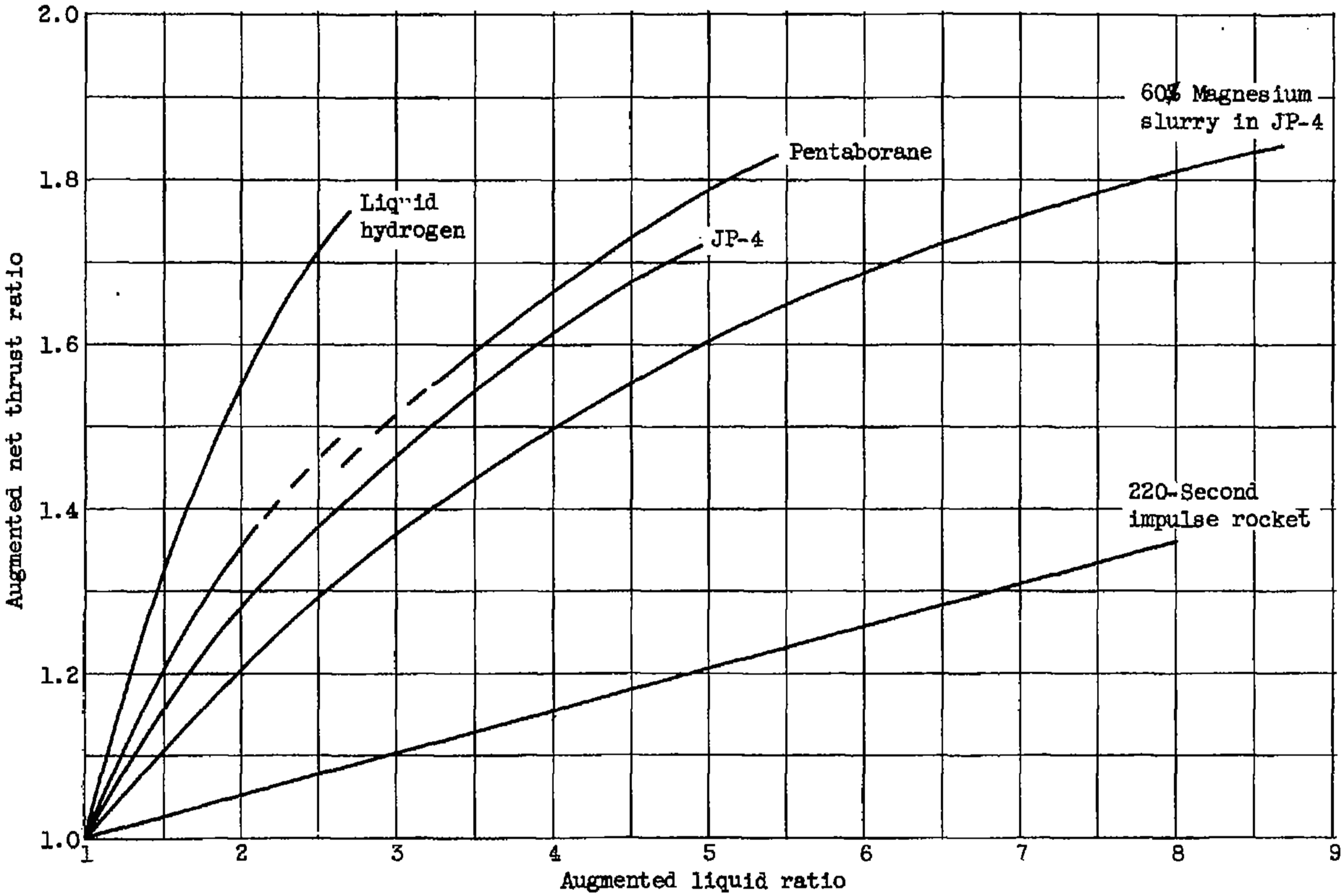

(c) Engine C; sea-level static conditions.

Figure 1. - Continued. Augmented ratios of net thrust and of liquid for four afterburner fuels and a rocket used with turbojet engines operating with choked convergent exhaust nozzles.

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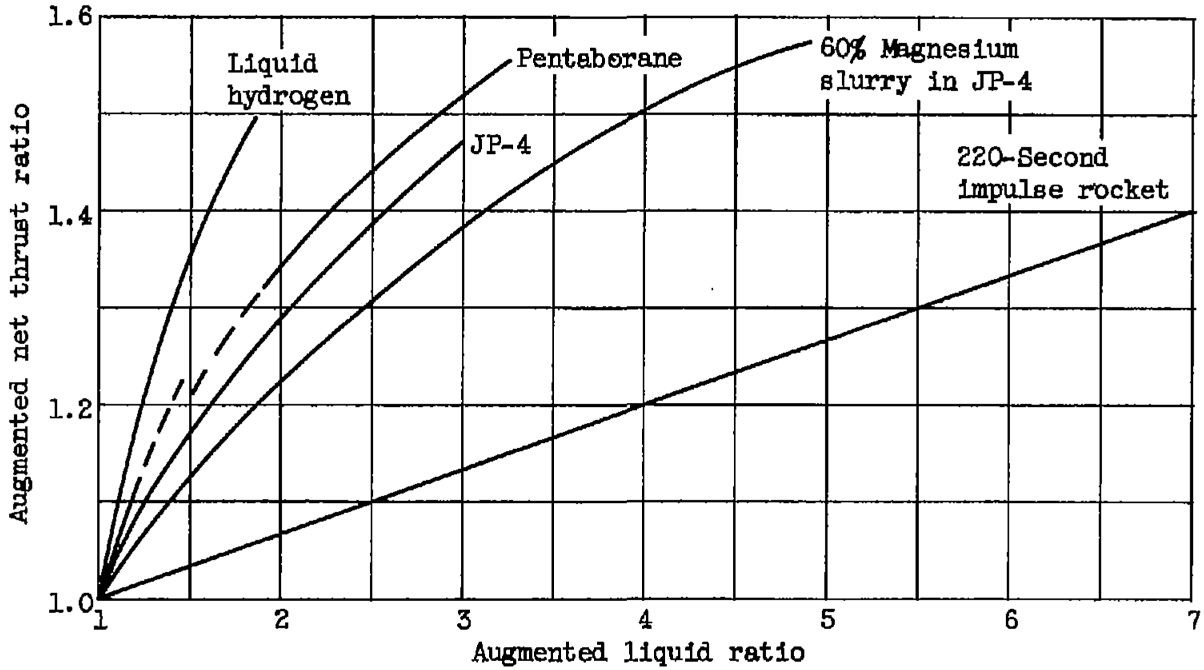

(d) Engine D; sea-level static conditions.

Figure 1. - Continued. Augmented ratios of net thrust and of liquid for four afterburner fuels and a rocket used with turbojet engines operating with choked convergent exhaust nozzles.

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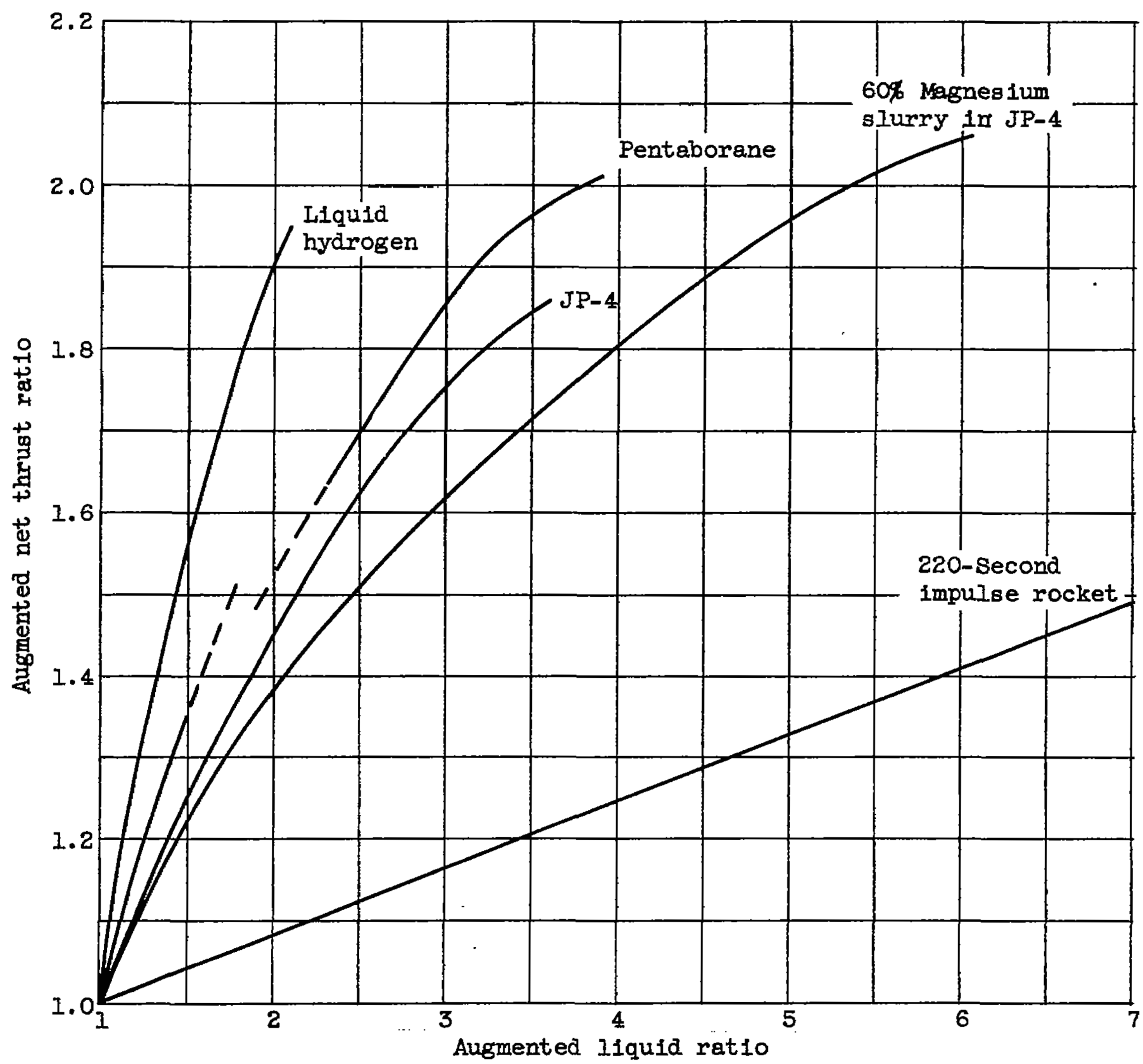

(e) Engine A; altitude, 50,000 feet; flight Mach number, 0.81.

Figure 1. - Continued. Augmented ratios of net thrust and of liquid for four afterburner fuels and a rocket used with turbojet engines operating with choked convergent exhaust nozzles.

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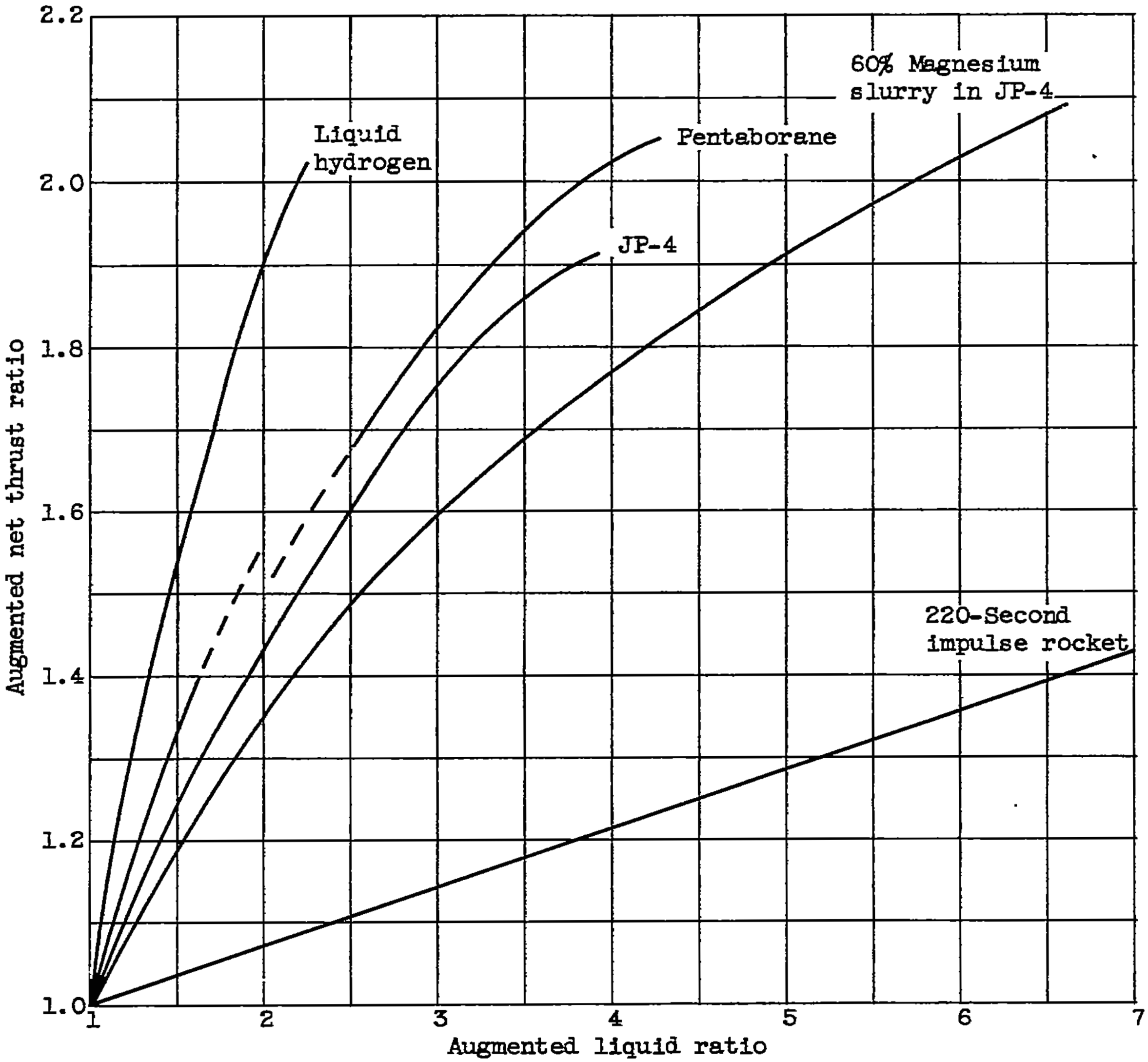

(f) Engine B; altitude, 50,000 feet; flight Mach number, 0.81.

Figure 1. - Continued. Augmented ratios of net thrust and of liquid for four afterburner fuels and a rocket used with turbojet engines operating with choked convergent exhaust nozzles.

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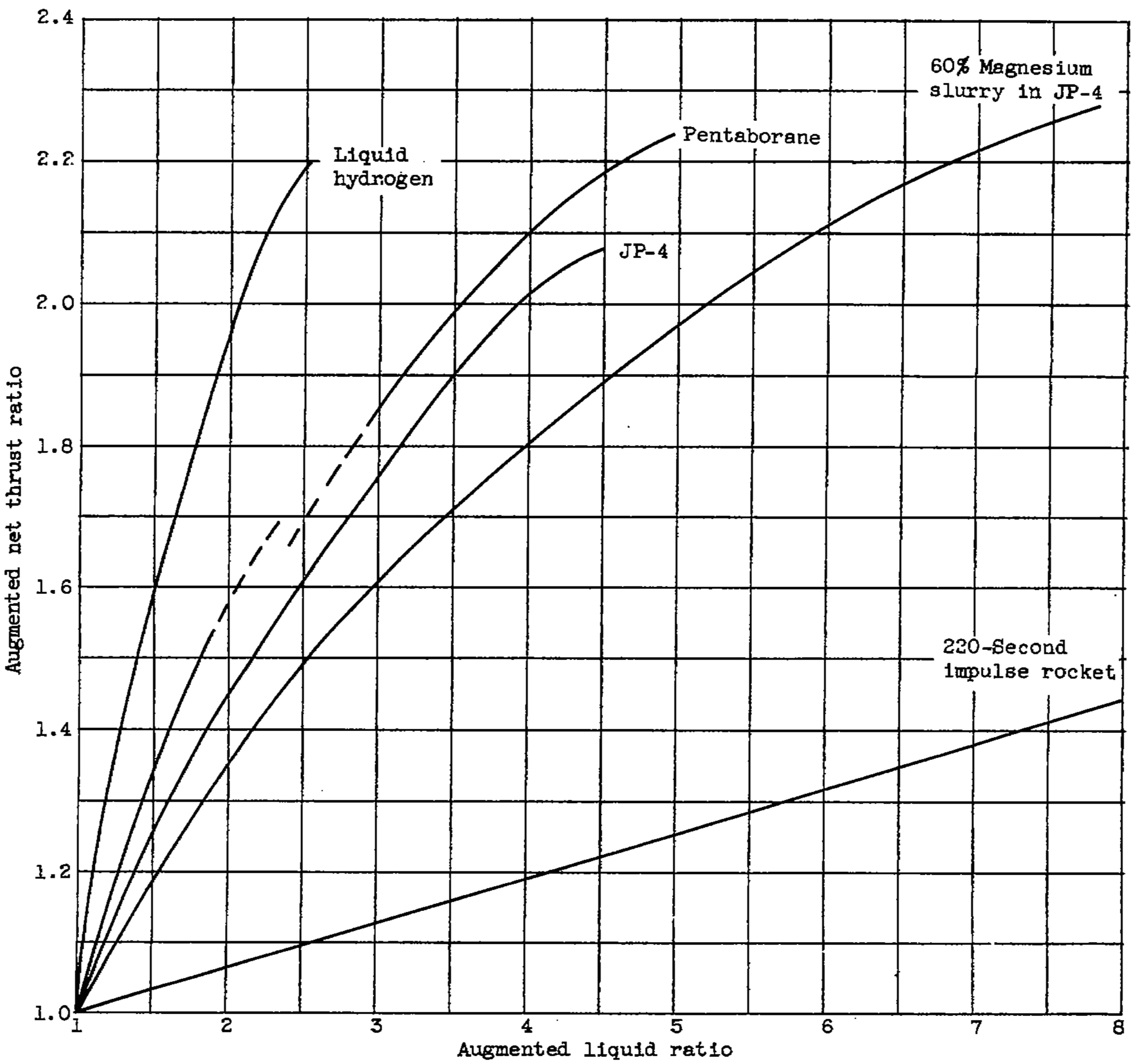
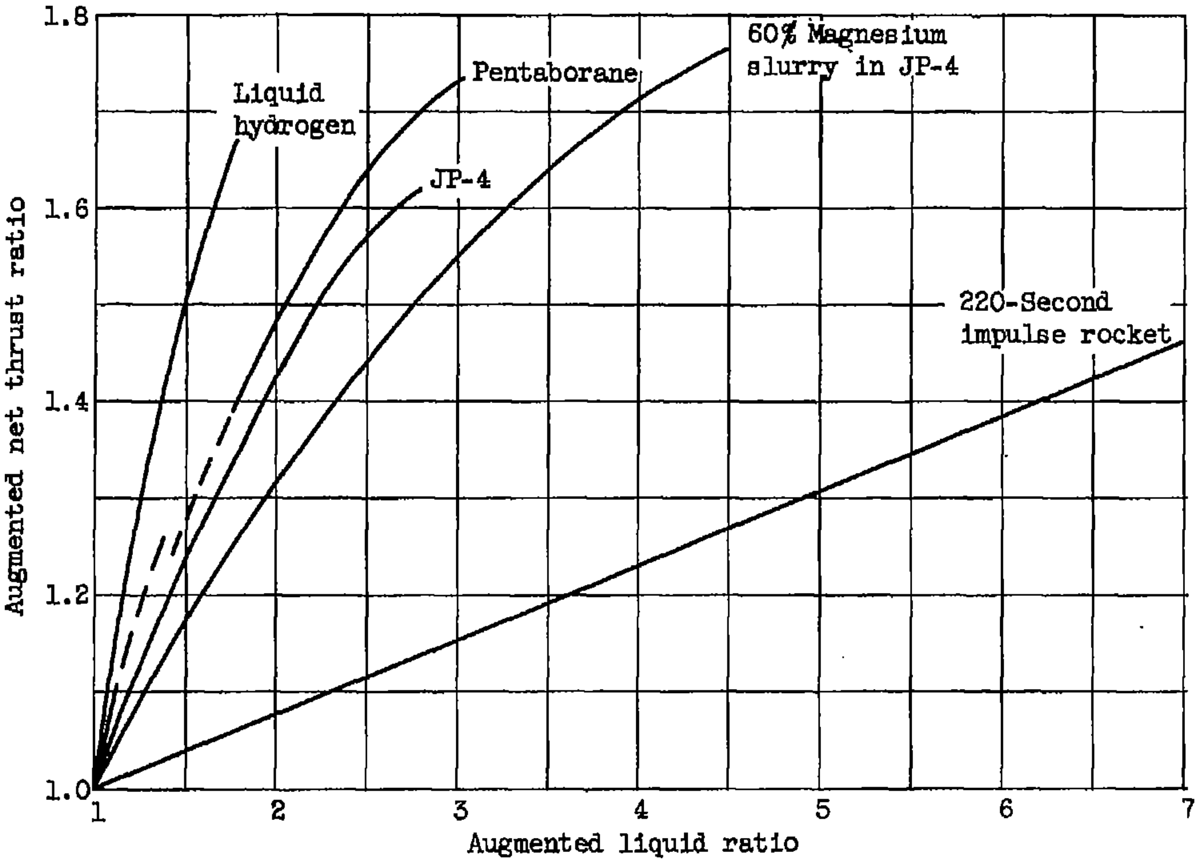


(g) Engine C; altitude, 50,000 feet; flight Mach number, 0.81.

Figure 1. - Continued. Augmented ratios of net thrust and of liquid for four after-burner fuels and a rocket used with turbojet engines operating with choked convergent exhaust nozzles.



(b) Engine D; altitude, 50,000 feet; flight Mach number, 0.81.

Figure 1. - Concluded. Augmented ratios of net thrust and of liquid for four afterburner fuels and a rocket used with turbojet engines operating with choked convergent exhaust nozzles.

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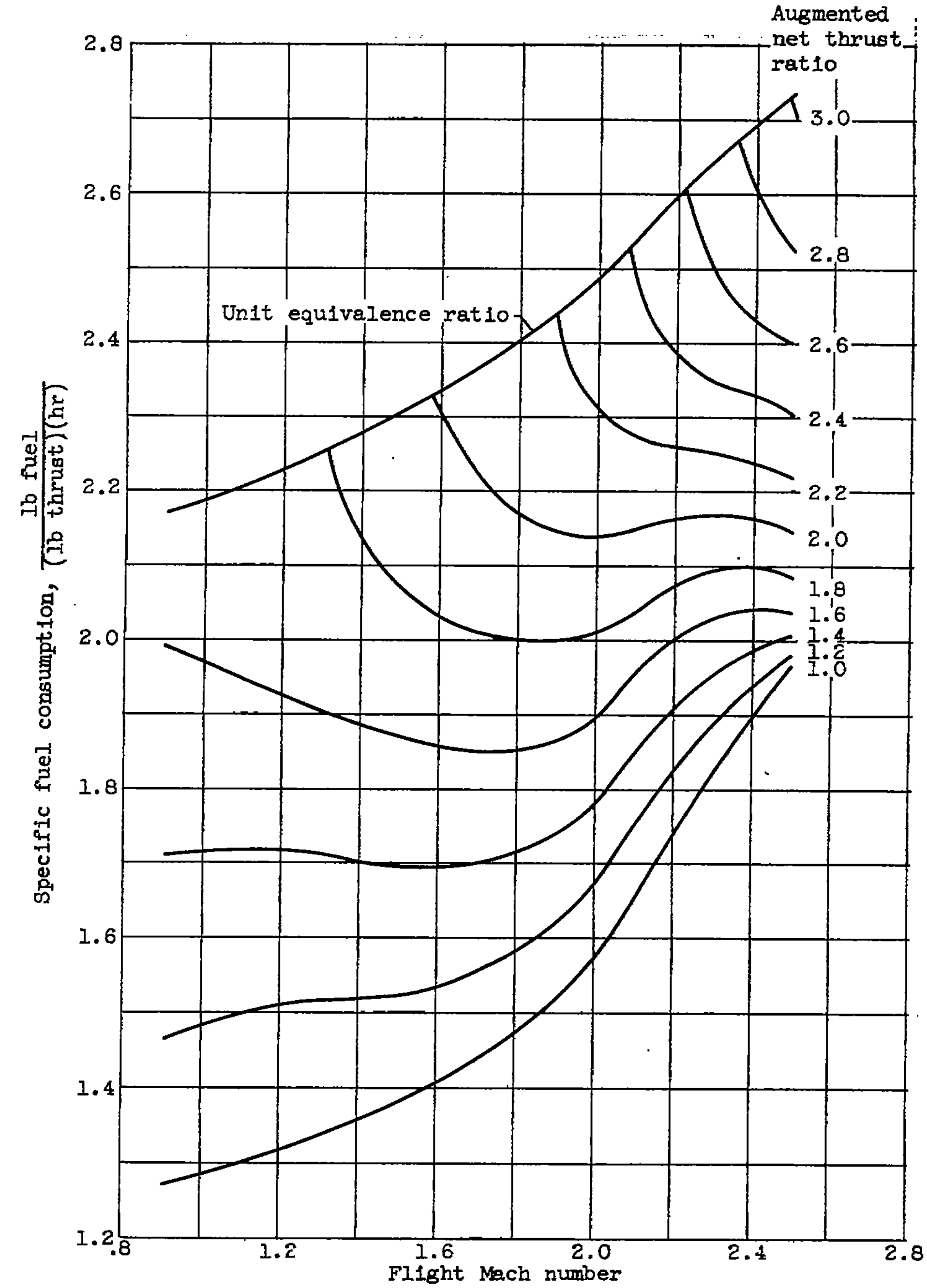

(a) Afterburner fuel, JP-4.

Figure 2. - Variations of specific fuel consumption and augmented net thrust ratio with flight Mach number for turbojet engine D operating with a choked convergent exhaust nozzle at altitude of 50,000 feet.

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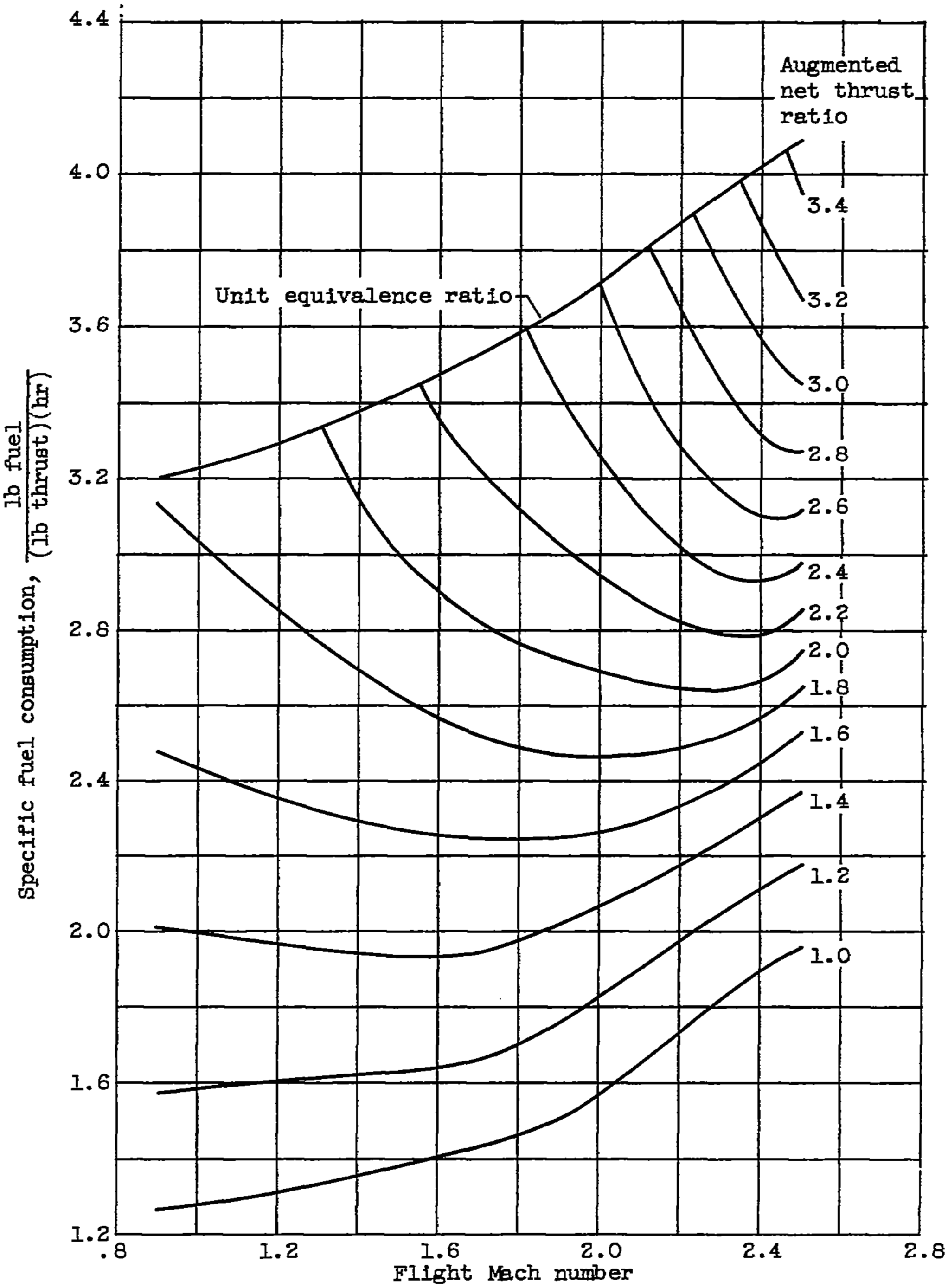

(b) Afterburner fuel, 60 percent magnesium slurry in JP-4.

Figure 2. - Continued. Variations of specific fuel consumption and augmented net thrust ratio with flight Mach number for turbojet engine D operating with a choked convergent exhaust nozzle at altitude of 50,000 feet.

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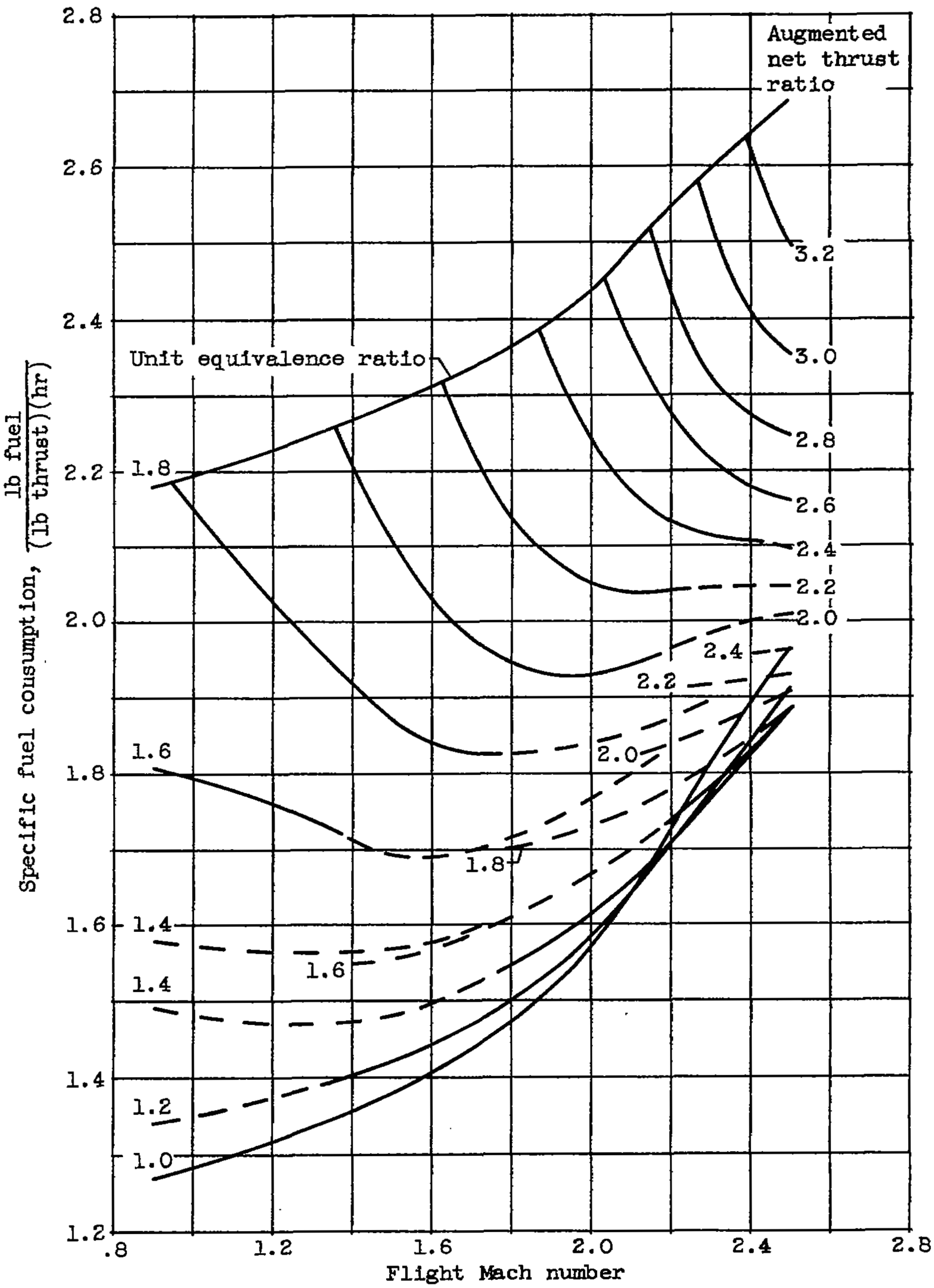

(c) Afterburner fuel, pentaborane.

Figure 2. - Continued. Variations of specific fuel consumption and augmented net thrust ratio with flight Mach number for turbojet engine D operating with a choked convergent exhaust nozzle at altitude of 50,000 feet.

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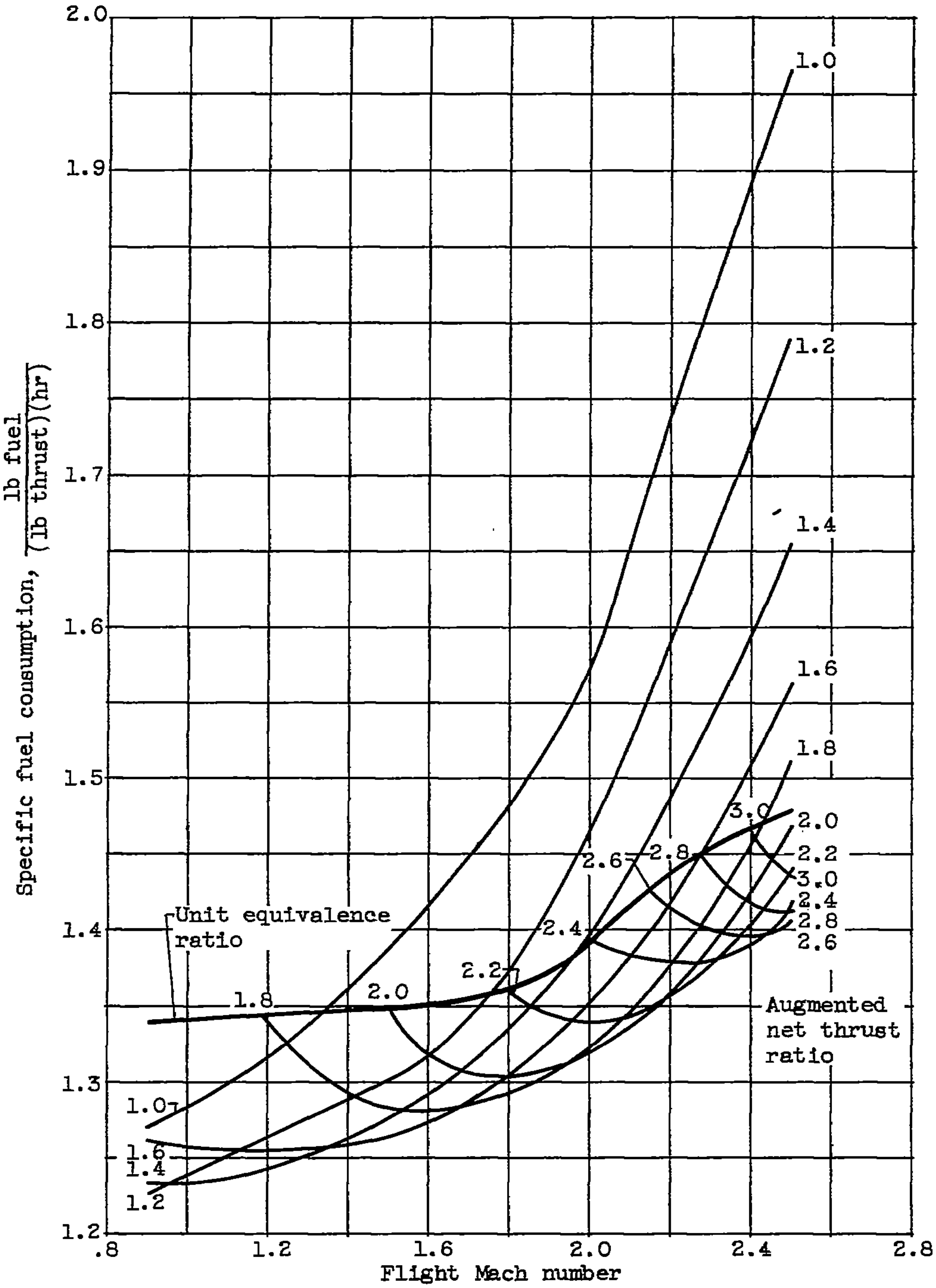

(d) Afterburner fuel, liquid hydrogen.

Figure 2. - Continued. Variations of specific fuel consumption and augmented net thrust ratio with flight Mach number for turbojet engine D operating with a choked convergent exhaust nozzle at altitude of 50,000 feet.

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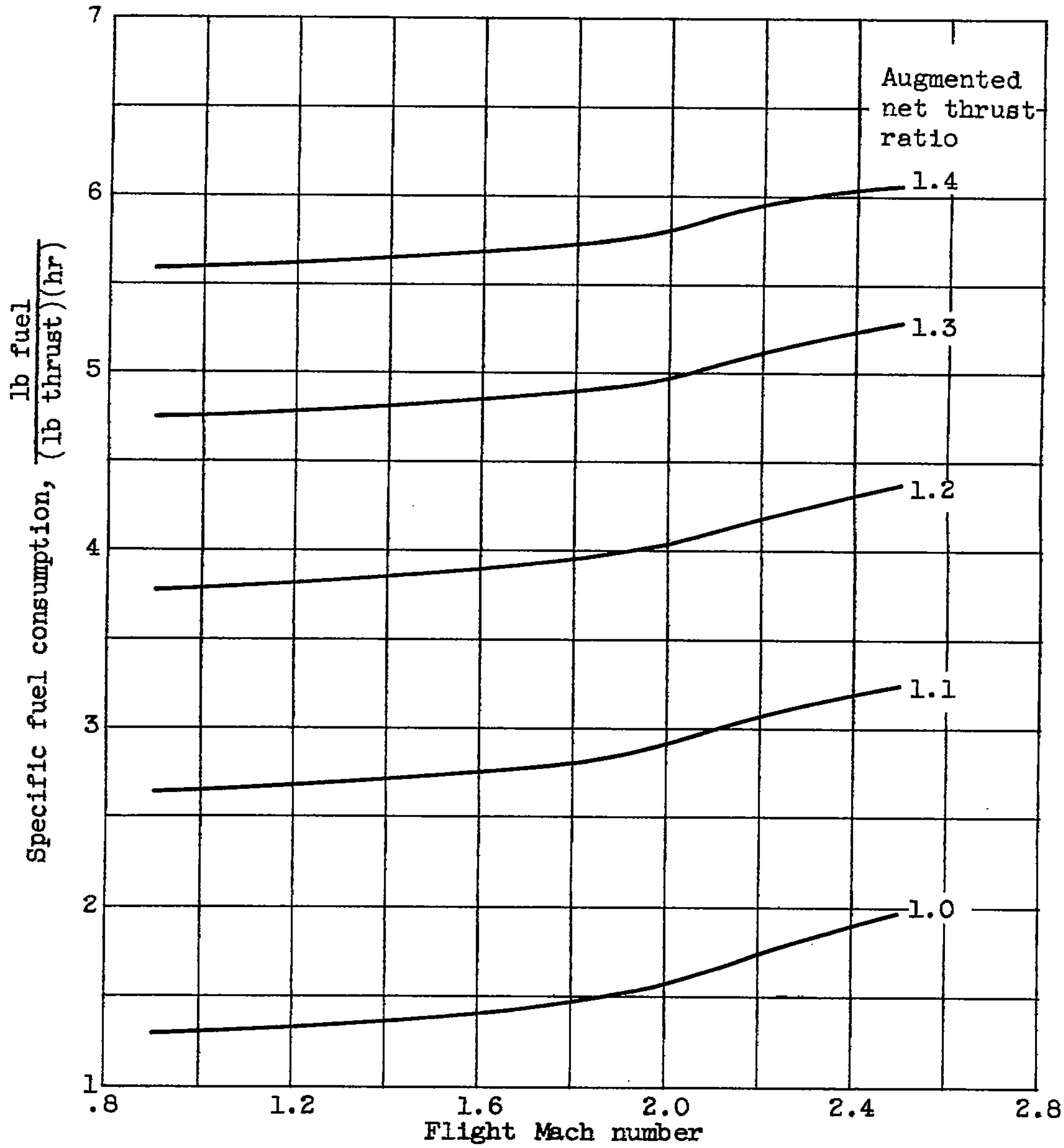

(e) 220-Second specific-impulse rocket.

Figure 2. - Concluded. Variations of specific fuel consumption and augmented net thrust ratio with flight Mach number for turbojet engine D operating with a choked convergent exhaust nozzle at altitude of 50,000 feet.

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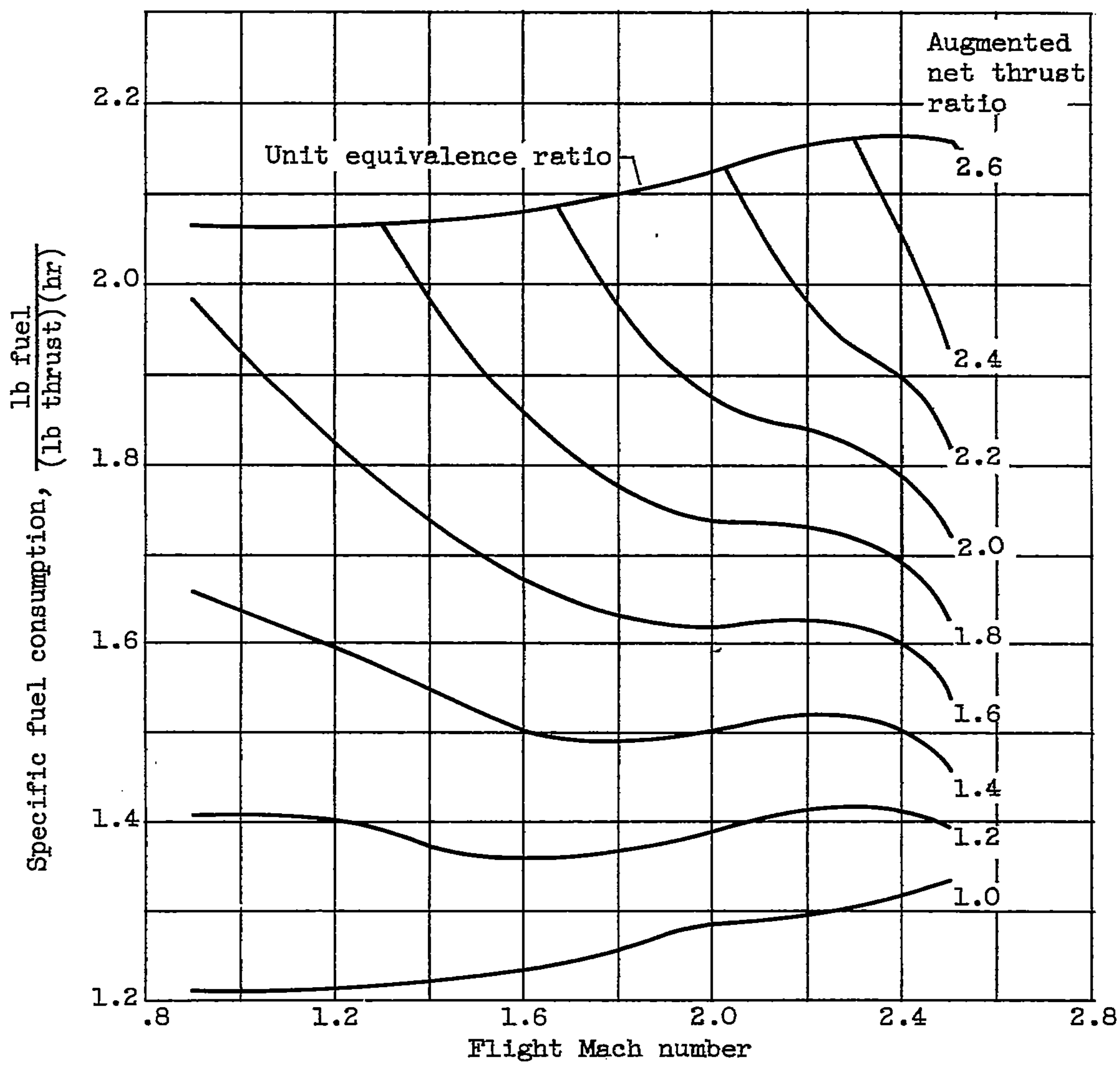
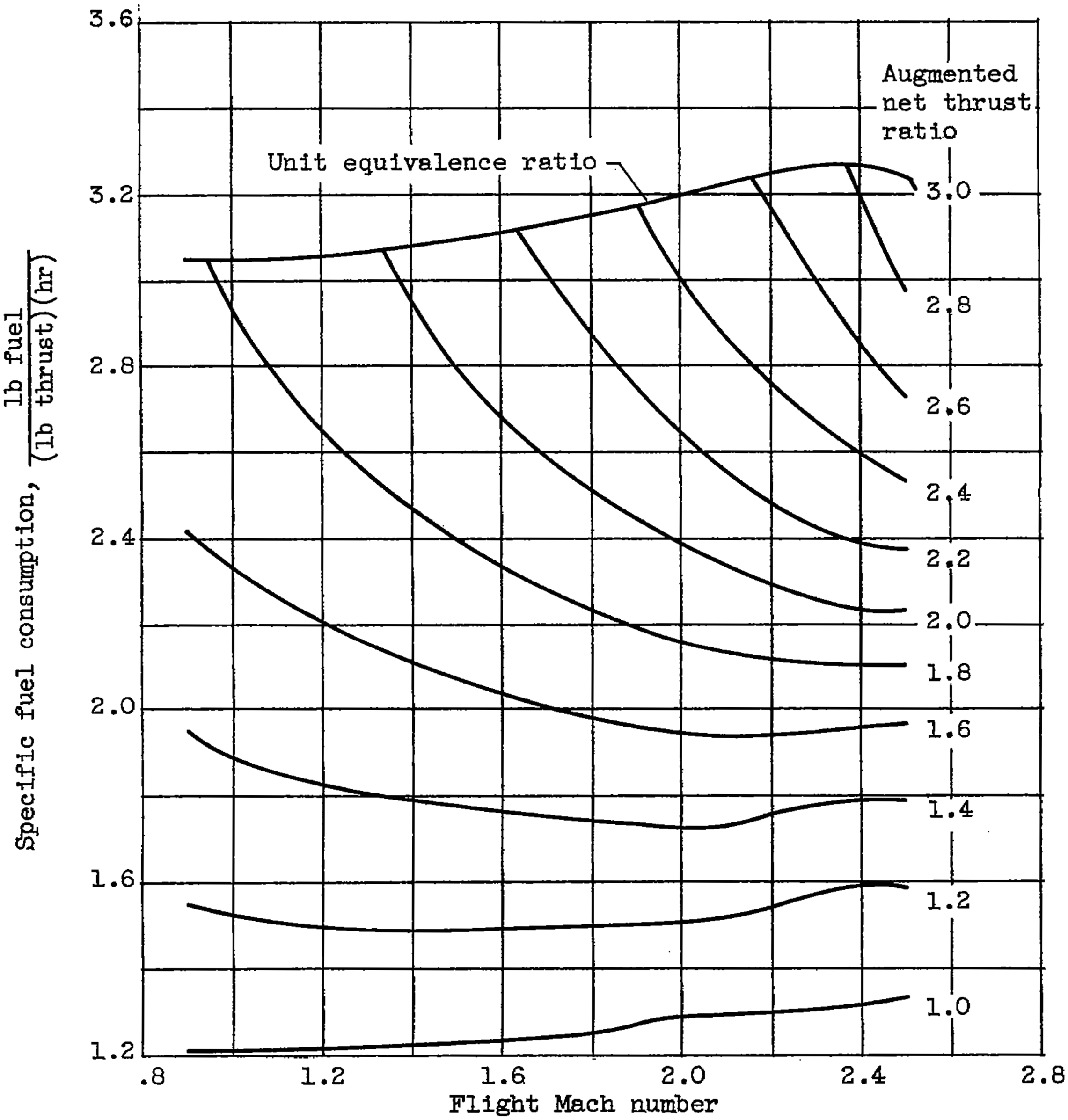


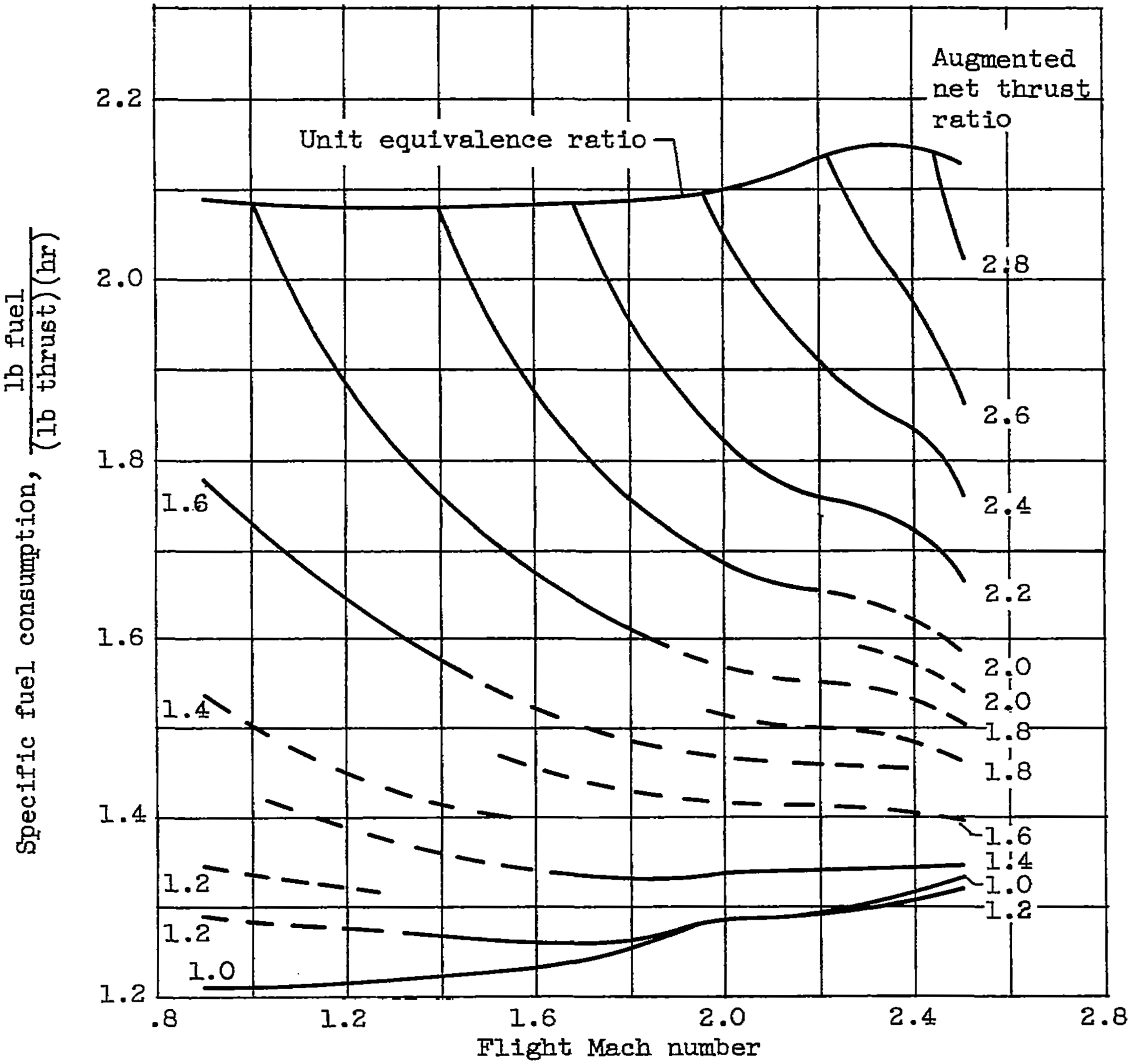
(a) Afterburner fuel, JP-4.

Figure 3. - Variations of specific fuel consumption and augmented net thrust ratio for complete expansion of exhaust products with flight Mach number for turbojet engine D at altitude of 50,000 feet.



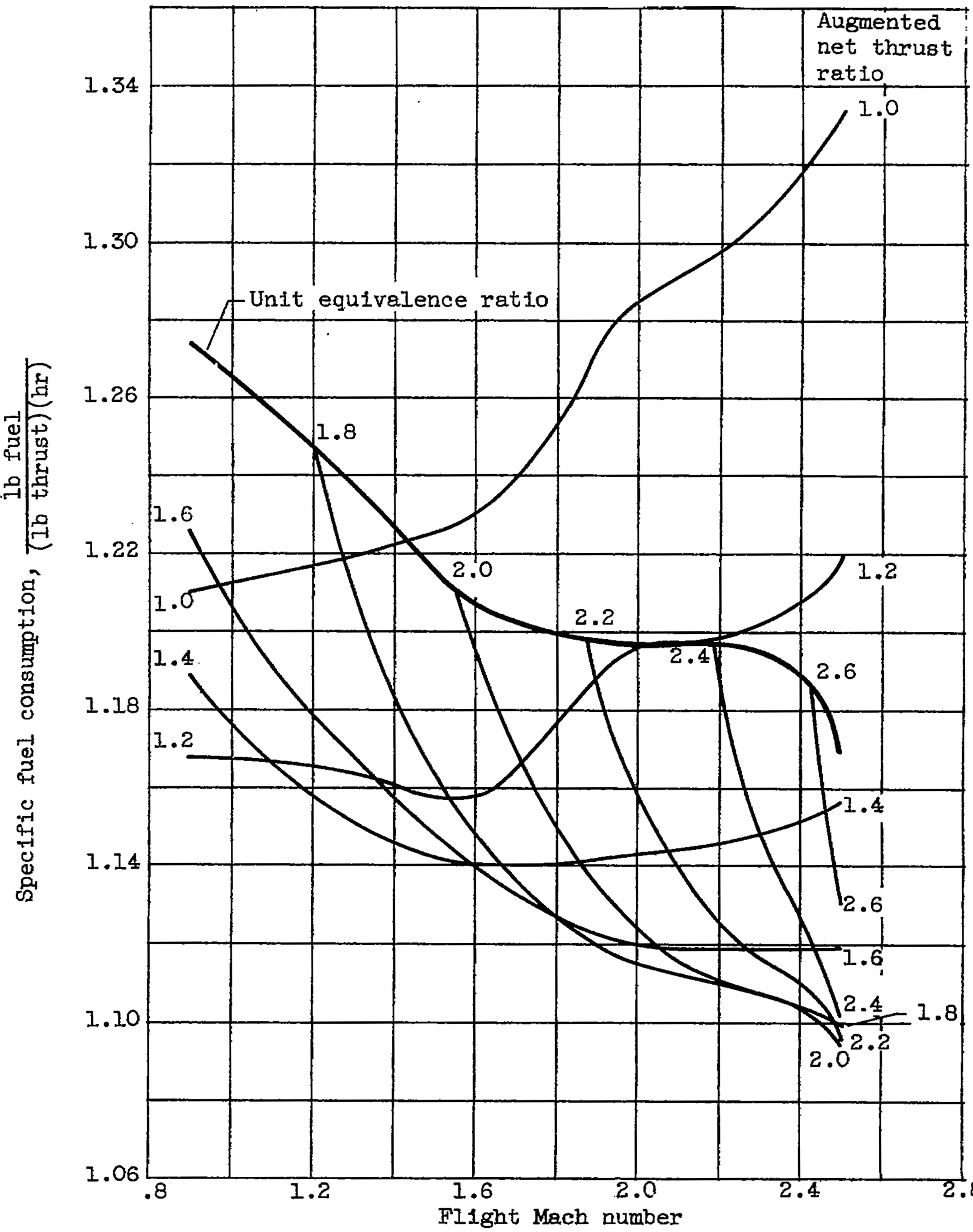
(b) Afterburner fuel, 60 percent magnesium slurry in JP-4.

Figure 3. - Continued. Variations of specific fuel consumption and augmented net thrust ratio for complete expansion of exhaust products with flight Mach number for turbojet engine D at altitude of 50,000 feet.



(c) Afterburner fuel, pentaborane.

Figure 3. - Continued. Variations of specific fuel consumption and augmented net thrust ratio for complete expansion of exhaust products with flight Mach number for turbojet engine D at altitude of 50,000 feet.



(d) Afterburner fuel, liquid hydrogen.

Figure 3. - Continued. Variations of specific fuel consumption and augmented net thrust ratio for complete expansion of exhaust products with flight Mach number for turbojet engine D at altitude of 50,000 feet.

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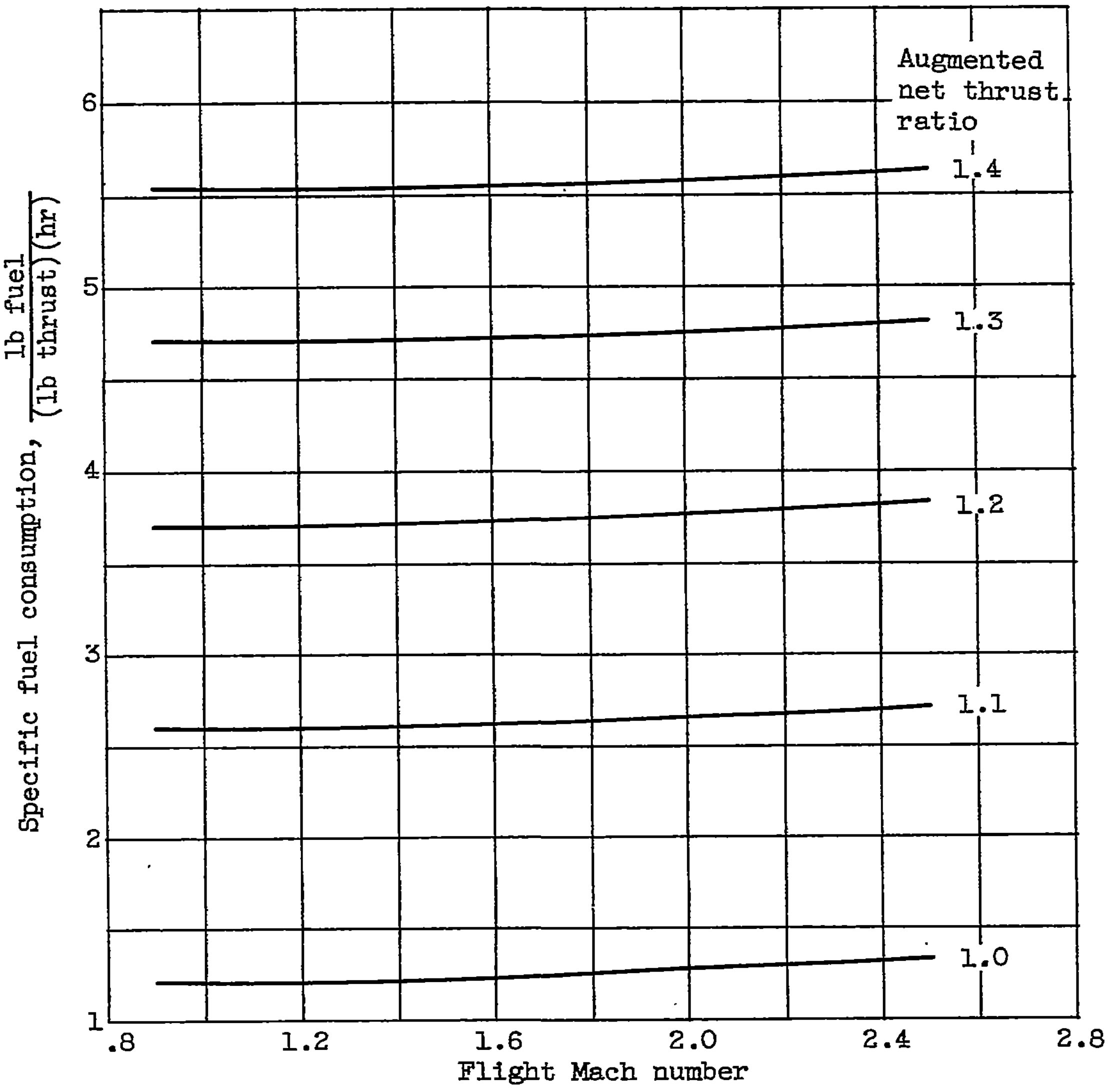

(e) 220-Second specific-impulse rocket.

Figure 3. - Concluded. Variations of specific fuel consumption and augmented net thrust ratio for complete expansion of exhaust products with flight Mach number for turbojet engine D at altitude of 50,000 feet.

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